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Published in:
Scandinavian Journal of Medicine & Science in Sports

DOI (link to publication from Publisher):
10.1111/sms.13027

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Silva, P. D. B., Oliveira, A. S., Mrachacz-Kersting, N., & Kersting, U. G. (2018). Effects of wobble board training on single-leg landing neuromechanics. *Scandinavian Journal of Medicine & Science in Sports*, *28*(3), 972-982. https://doi.org/10.1111/sms.13027

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Article type : Original Article

EFFECTS OF WOBBLE BOARD TRAINING ON SINGLE-LEG LANDING NEUROMECHANICS

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Running title: Balance training influences landing control

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/sms.13027

ABSTRACT

Balance training programs have been shown to reduce ankle sprain injuries in sports, but little is known about the transfer from this training modality to motor coordination and ankle joint biomechanics in sport specific movements. This study aimed to investigate the effects of wobble board training on motor coordination and ankle mechanics during early single-leg landing from a lateral jump. Twenty-two healthy men were randomly assigned to either a control or a training group, who engaged in four weeks of wobble board training. Full-body kinematics, ground reaction force and surface electromyography (EMG) from 12 lower limb muscles were recorded during landing. Ankle joint work in the sagittal, frontal and transverse plane were calculated from 0-100 ms after landing. Non-negative matrix factorization (NMF) was applied on the concatenated EMG Pre- and Post-intervention. Wobble board training increased the ankle joint eccentric work 1.2 times in the frontal ($p<0.01$) and 4.4 times in the transverse plane ($p<0.01$) for trained participants. Wobble board training modified the modular organization of muscle recruitment in the early landing phase by separating the activation of plantar flexors and medio-lateral ankle stabilizers. Furthermore, the activation of secondary muscles across motor modules was reduced after training, refocusing the activation on the main muscles involved on the mechanical main sub-functions for each module. These results suggest that wobble board training may modify motor coordination when landing from a lateral jump, focusing on the recruitment of specific muscles/muscle groups that optimize ankle joint stability during early ground contact in single-leg landing.

Key words: balance training; injury prevention; motor modules; muscle synergies; ankle; stability

INTRODUCTION

Landing on one leg is common in team sports[1], and an adequate landing technique is crucial to optimize load distribution and cope with potentially destabilizing force components.[2,3] In game situations, landing becomes more challenging by the interaction of mechanical and cognitive demands as they occur[4], possibly increasing the risk of injuries. In fact, jump-landing sequences in basketball and volleyball have been linked to 45–86% of acute ankle and knee sprains[5], which can be related to the high postural demands and cognitive-motor interactions that challenge postural control when landing from a jump.[5] It has been demonstrated that the direction of the jump significantly affects lower limb net joint moments, as these are up to 10 times higher during lateral drop jumps compared to other directions.[6]

The above mentioned greater demands that lateral and diagonal jumps induce to dynamic postural stability during landing can further challenge the motor control of multi-joint coordination to dissipate energy[7]. Inter-muscular coordination is a term used in sports sciences and sports medicine to describe neuromuscular mechanisms for movement control. Inter-muscular coordination has been investigated using different processing methods based on surface electromyographic (EMG) parameters from individual muscles or selected muscle groups.[8,9] This selection of specific muscles compromises the comparability of results across studies and may impede the identification of a potentially superordinate strategy. Therefore, it is important to establish robust methods for investigating muscle coordination in complex movements. The use of non-negative matrix factorization (NMF) allows for the extraction of inter-muscular relationships from EMG data over time. NMF has been used to describe neural control of movement and inter-muscular coordination in sports[10] and postural control.[11,12] Therefore, factorization analysis may be a suitable methodology to describe motor coordination during lateral landing by identifying the same mechanical goals and sub-functions of a group of muscles during different tasks.[13]

Previous studies have shown the effectiveness of balance training in reducing lower limb injury occurrence. It is believed that motor coordination is a key factor for injury prevention, as the gains in inter-muscular coordination for landing may potentially reduce the likelihood of lower limb injuries. Wobble boards are simple and low-cost devices widely used to investigate [14,15] and improve balance and postural control.[16,17] Previous studies have shown that such devices can provide fast improvement in balance performance with a long-term retention, [18,19] ultimately reducing the risk of ankle sprains by up to 50%.[20] Moreover, athletes presenting poor neuromuscular landing technique have been found to be less efficient to dissipate energy[9] and more prone to knee and ankle injuries.[21] These observations taken together suggest that the adaptations acquired from specific balance exercises seem to be transferred to motor control of movements with high injury risk, such as those involving single-leg landing.

There is a lack of studies demonstrating the neuromechanical changes induced by balance training during sports movements. Additionally, the few existing studies that report neuromuscular adaptations from balance training transferred to landing have reported localized benefits predominantly at the knee joint.[22] Therefore, the aim of the present study was to investigate whether the gains in balance skills induced by wobble board training would be transferred to lateral landing by means of improvements in lower limb inter-muscular coordination and ankle mechanics. It was hypothesized that balance training would alter the modular organization of muscle recruitment during early ground contact of lateral landing. This change in inter-muscular coordination would influence the ankle mechanics and increase the joint work related to medio-lateral stability of the ankle.

METHODS

Participants

Twenty-four healthy young men (18-25 years old) volunteered for the study. Initially, participants filled in the Cumberland Ankle Instability Tool (CAIT) questionnaire[23], which is largely used to identify functional ankle instability. Exclusion criteria included a CAIT-Score under 27.5, history of lower-extremity injury, recent (within the last 6 months) low back injury, and/or vestibular dysfunction, as well as previous experience and/or systematic training using a wobble board. Leg dominance was determined through three functional tests: ball kick test, step-up test and balance recovery test.[24] The participants in this study were recreational practitioners of different team sports (soccer, basketball, handball, volleyball). Participants reported to partake in physical activities about 3-5 times per week. All participants provided written informed consent before participation and the procedures were approved by the ethical committee of Northern Jutland (N-20120044).

Experimental design

All participants took part in a familiarization session that included: 1) filling out the CAIT- Questionnaire; 2) determination of leg dominance; 3) explanation of the experimental procedures; 4) practice of lateral jumps and 5) determination of the maximal lateral jumping height, which was defined as the target jump height for the subsequent data collection sessions. The maximal jump height was defined as the maximal height participants could reach while being able to land and stop without taking extra steps on the force platform. A second session (experimental session) took place on a following day up to 72 hours after the familiarization session for the recordings of EMG and kinematic data from lateral jumps. Experimental sessions were conducted before (Pre) and after (Post) training. Training group (TG) participants also took part in 12 intervention sessions (T1-T12, 30 min duration, 3 sessions/week – see section Training intervention) over four weeks. Participants allocated to the control group (CG) were asked to maintain their normal activity during the four weeks between sessions.

Lateral jump task

Initially, the target bar (Figure 1A) was positioned according to the maximal height reached in the familiarization session. In this study, the landing phase of the jump was analysed, therefore the target bar was fixed at the same height before and after the training to minimize potential technique changes related to jump performance. Participants then performed 5 to 10 warm-up/familiarization trials, followed by 10 recording trials. The lateral jump initial position was individually adjusted to allow for one lateral step before the jump, which consisted of a sidestep with a push off sideways with the participants aiming at touching the target bar with both hands and land with their dominant foot on the force plate and stop (Figure 2A). A jump trial was discarded if the subject required any stepping corrections following landing as described above. All participants were barefoot during testing, and none reported any discomfort that would limit the execution of the functional tasks.

INSERT FIGURE 1 HERE

Training intervention

Training sessions consisted of 15 balance exercises using a WB performed intermittently with 60 s of exercise and 60 s rest in between. Single-leg standing on the WB with hands akimbo was the initial position for all the exercises. Progression of the level of difficulty was provided once the participants accomplished the task without failing to stand on one leg for 20 consecutive seconds.

Levels of difficulty performed were as follows: 1. standing still looking straight ahead; 2. rocking the board in the sagittal plane; 3. rocking the board in the frontal plane; 4. rocking the board alternately in the frontal and sagittal planes; 5. tilting the head sideways repeatedly; 6. tilting the head anteriorly and posteriorly; 7. performing selected arm movements; 8. performing contra-lateral leg movements; 9. combining leg and arm movements; 10. performing single-leg squats; 11. bouncing a ball on the floor; 12. throwing a ball against a target on the wall and catch; 13. performing volley taps of an air balloon; 14. keeping eyes closed; 15. performing tasks 1 to 14 using a hemi-sphere with a smaller diameter mounted to the board.

Data collection

Kinetics

A three-dimensional force platform (AMTI, OR6-5, Watertown, MA) provided ground reaction forces (GRF) and moments sampled at 1000 Hz, simultaneously with marker data by a motion capture system (8-cameras, Oqus 300, Qualisys, Gothenburg, Sweden) at 250 Hz. The GRF data were filtered with a fourth-order 100 Hz low-pass zero-lag Butterworth filter. The peak GRF was computed for both the vertical and lateral force components.

Kinematics

Retro-reflective, markers were attached bilaterally to the skin overlying the following anatomical landmarks: heel, first and fifth metatarso-phalangeal joint, lateral malleolus, lateral knee condyle, greater trochanter, anterior and posterior superior iliac spines and acromio-clavicular joints. Markers were placed also on manubrium, xiphoid process, spinal process tip of the seventh cervical vertebrae. Additional markers were placed on the segments (foot, shank, thigh), serving as tracking markers to define the three-dimensional (3D) motion for the dominant limb segments.[25]

Marker trajectories from the motion analysis collection were low pass filtered at 10 Hz with a recursive fourth order Butterworth digital filter. Three-dimensional data from trunk, pelvis and lower limbs were used to calculate center of gravity, using rigid body analysis (Visual3D, Version 5, C-Motion, Inc., Rockville, MD). Jump height was calculated as the difference between pelvis height while standing and the maximum vertical position during the flight phase of the jump-landing task.

EMG

For recording EMG signals, bipolar derivations with pairs of Ag/AgCl electrodes (AmbuNeuroline 720 01-K/12; Ambu, Ballerup, Denmark) with 22 mm of center-to-center spacing were used. Prior to electrode placement, the skin was shaved and lightly abraded. The EMG signals were recorded from the following muscles of the landing leg – dominant side - according to Barbero et al.[26]: tibialis anterior (TA), peroneus longus (PL), soleus (SO), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), gluteus maximus (GMax) and gluteus medius (GMed). A reference electrode was placed over the left tibial bone. The EMG cables were held tightly close to the lower limb segments by stretching running pants, in order to minimize movement artefacts during jumping and landing. The EMG signals were sampled at 2000 Hz (12 bits per sample - Biovision, Wehrheim, Germany), band-pass filtered (second-order, zero lag Butterworth, bandwidth 10–500 Hz) and recorded on the computer's storage medium for off-line analysis.

Data analysis

Ankle Joint Mechanics

The position and orientation of the right ankle joint was calculated using an inverse kinematic lower limb model created in Visual 3D (C-motion, Germantown, MD). The ankle joint was constrained to have three rotational degrees of freedom (DOF), the x-axis represented dorsiflexion/plantarflexion, the y-axis represented inversion/eversion and the z-axis represented abduction/adduction of the foot in relation to the lower leg. Neutral ankle joint position were 0 degree in the frontal, transversal and sagittal planes. Positive values correspond to dorsiflexion, eversion and abduction. Instantaneous ankle joint power trajectories were computed for the landing period. Joint power was normalized to body mass. Instantaneous ankle joint power trajectories were computed from within 100 ms post initial contact. Ankle joint work was obtained by quantifying the integral of the joint power-time curve. By convention, the magnitude of joint work is proportional to the active muscle work around the joint, while positive and negative power values would indicate energy generation and absorption.[3]

Surface EMG segmentation

The jump cycle was defined from 200 ms prior to initial contact (defined from the vertical GRF) to 200 ms after the minimal pelvis position following initial foot contact. After segmentation, the surface EMG signals from the 12 muscles were low-pass filtered (20 Hz), full-wave rectified and time-normalized in order to obtain 200 data points for each landing.[27,28] For each subject, the individual EMG amplitudes were normalized for each trial to the respective peak EMG, therefore varying from 0 to 1 (Figure 1B illustrates the single trial EMG signals). In both Pre- and Post-training datasets, the EMG trials were averaged for each subject, so that they represented each subject by one averaged lateral jump EMG matrix. Subsequently, we concatenated the EMG data from all participants of the TG and CG into pre-training and post-training datasets. In this manner, inter-subject variability was accounted for in the analysis.[29]

Non-negative matrix factorization

NMF was applied in each of the concatenated datasets to identify muscle weightings (motor modules) and activation signals. There is a detailed description elsewhere of the motor modules model used, calculation of dimensionality and motor modules similarities.[27,28] Briefly, after extracting the motor modules, the estimated muscular activation pattern was compared with the recorded pattern by means of the variance accounted for (VAF) value, defined as the variation that can be explained by the model: VAF = 1 – SSE/SST, where SSE (sum of squared errors) is the unexplained variation and SST (total sum of squares) is the pooled variation of the data. The reconstruction quality was analysed by plotting the VAF as a function of the number of modules, and the minimum number of modules was identified as the point in which this curve pronouncedly changed its slope.[30] A second criterion was that reconstruction quality should achieve at least 80% for the concatenation of multiple participants.[27,31]

Motor modules similarities

In order to quantitatively compare the muscle weightings results from Pre- to Post-training, as well as the activation signals across all participants, an index of similarity was computed. Similarities between muscle weightings or activation signals were calculated computing scalar products between pairs of columns, normalized by the product of the norms of each column.[28,30] A pair of muscle weightings or activation signals was considered similar if the scalar products were ≥ 0.8.[28,31]

Residual muscle weighting

The use of NMF for exploring neural control of movement implies that a group of muscles are predominantly active in a motor module. Therefore, these same muscles should present minimal activation in other motor modules. In this study, we introduced the calculation of residual muscle activation (RMW). For each muscle, the motor module presenting the highest muscle weighting was set to 100% and all other weightings of other motor modules were converted to a fraction of the maximum. The RMW for a given muscle as defined as the sum of the normalized muscle weightings across all motor modules, except from the module presenting the highest weighting. The RMW was calculated for each muscle Pre- and Post-training for both CT and TG.

Statistical analysis

The Statistical Package for the Social Sciences (IBM SPSS Inc. Version 22.0, Chicago, IL, USA) was used for statistical analysis. To evaluate the effects of training on the motor modules and activation signals, similarities between pre- and post-training conditions were computed for the TG and CG separately. Repeated measures 2-way analysis of variance (ANOVA), considering two groups (TG vs CG - between subject factor) and two time levels (Pre vs Post - repeated measures factor) was used to verify significant group-by-time interactions as well as simple main time effects of the jump height, peak of ground reaction forces, RFD, ankle joint work, motor modules VAF, inter-participants similarity, and muscle weightings RMW. Bonferroni pairwise *post-hoc* tests were used in case of significant group-by-time interactions. Partial eta-squared (ηp^2) was used to calculate the treatment effect sizes. The significance level was set at $p<0.05$. All dependent variables demonstrated a normal distribution and the average statistical power ranged from 0.52-0.92. The significance level was set at $p<0.05$. Data are displayed as mean±standard deviation (SD).

RESULTS

Two participants reporting a low CAIT-Score were excluded, while two participants chose to withdraw from the study. Therefore, nine participants assigned to a control group (CG, CAIT-Score 28.2±0.9; age 26±3 years old; BMI=22.9±1.4) and 11 participants assigned to the training group (TG, n=11: CAIT-Score 28.8±1.2; age: 25±2 years old; BMI=21.9±2.0) completed the experiment.

Lateral jump and landing performance

No significant group-by-time interactions were observed for lateral jump height, vertical or lateral peak ground reaction force (p=0.365, ηp^2 = 0.048; p=0.43, ηp^2=0.03; p=0.13, ηp^2=0.12, respectively; Table 1). Likewise, no significant group-by-time interactions were observed for lateral jump height, vertical or lateral RFD (p=0.365, ηp^2 = 0.048; p=0.843, ηp^2 = 0.002; p=0.630, ηp^2 = 0.013, respectively; Table 1).

INSERT TABLE 1 HERE

Ankle joint mechanics

A significant group-by-time interaction was observed for the ankle plantar flexion angle at initial contact (DF: p=0.04, ηp^2=0.22, ADD: p=0.680, ηp^2= 0.01; INV: p= 0.664, ηp^2=0.01; Figure 2 A, C and F). Bonferroni post-hoc tests revealed no significant difference Pre- and Post-training (CG: p=0.130, ηp^2=0.21; TG: p=114, ηp^2=23). Participants from the control and training group landed with about 42.5 degrees of plantar flexion four weeks after the initial experimental session. Considering that no main time or group effects were observed (p=0.61, ηp^2= 0.01; p=0.32, ηp^2= 0.05, respectively), this represents a non-significant increase in plantar flexion for the control and a non-significant decrease in plantar flexion for trained participants.

A significant group-by-time interaction was observed for inversion and adduction ankle joint work (dorsiflexion: $p=0.279$, $\eta p^2=0.06$, adduction: $p=0.007$, $\eta p^2= 0.33$; inversion: $p= 0.007$, $\eta p^2=0.34$; Figure 2, B, D and E). Bonferroni *post-hoc* tests revealed that the TG increased both ankle eversion and abduction work (adduction: $p=0.04$, $\eta p^2= 0.37$; inversion: $p=0.03$, $\eta p^2=0.39$) after training. No changes in ankle work was found for the CG (adduction: $p=0.09$; $\eta p^2= 0.32$; inversion: $p=0.104$, $\eta p^2=$ 0.30).

INSERT FIGURE 2 HERE

Motor modules - Dimensionality

Six to seven motor modules (M) were sufficient to reconstruct multi-muscle EMG for both CG and TG. The reconstruction quality using less than six modules was below 78%, whereas this quality using six motor modules was 88±0.02% (5.0±0.8% contribution to the VAF). The addition of a seventh motor module only raised the reconstruction quality to 90±0.007%, which was a contribution of only 3.3±0.3% to the VAF. Therefore, further analyses were based on six motor modules from all participants. No significant group-by-time interactions nor main effects were found for the VAF from the CG (VAF Pre = 91±0.01%; VAF Pre = 90±0.01%) and TG (VAF Pre = 92±0.02%; VAF Pre = 90±0.01%).

Motor modules describing inter- muscular coordination during landing

The module with predominant gluteal muscle function (M4) was active about 50 ms prior to landing, likely acting to align the lower limb and preparing the hip joint for initial contact. Immediately after landing, the first peak of activation signals corresponded to the muscles that stabilize the ankle joint in the frontal and sagittal planes (M1). The M2 presented generalized co-activation of several muscles with inconsistent patterns across groups pre- and post-training, likely to stabilize joints after initial contact. Approximately halfway through the absorption period, knee (M3) and hip extensors (M4) were predominantly active likely responsible to generate joint torques and dissipate energy. The other two modules (M5 and M6) were active throughout the whole landing phase, indicating that they were functioning to stabilize the joints rather than dissipating energy.

INSERT FIGURE 3 HERE

Similarities

The similarities between muscle weightings extracted pre- and post-training were >0.8 for all modules, except for M2 and M6 of the CG and M1 and M2 of the TG (Figure 4A). Regarding the activation signals, the similarity between pre- and post-training was >0.85 for all modules in both groups. Moreover, the similarities between the activation signals were significantly higher in comparison to the similarities between muscle weightings ($p<0.05$, $\eta p^2 = 0.17$).

Residual muscle weighting

There was significant group-by-time interaction ($p<0.05$, $\eta p^2 = 0.17$) for RMW, Bonferroni *post-hoc* tests revealed that RMW was significantly smaller (~30%) for TG

Post-training in comparison to TG pre-training ($p<0.01$) while CG Pre- and Post-training did not differ ($p=0.923$). In Figure 3, the muscle weightings from the TG are shown on the right side, where a reduction in the size of the weighting for individual muscles across modules becomes evident, as each muscle reaches a higher relative amplitude concentrated in the module where it is predominantly active.

INSERT FIGURE 4 HERE

DISCUSSION

The main findings of this study were that wobble board training increased early landing eversion and abduction joint work. Concomitantly, the training modified the modular organization of muscle recruitment during early contact, separating one module with main activation of gastrocnemius muscles and another for the main activation of tibialis anterior and peroneus longus. The wobble board training reduced the activation of secondary muscles across motor modules, concentrating the activation on the main muscles involved in the mechanical sub-functions for each module. Taken together, these results suggest that wobble board training may modify motor coordination for landing from a lateral jump, focusing on the recruitment of specific muscles/muscle groups that optimize ankle joint stability during the early contact of single-leg landing.

Ankle sprain injuries are rarely recorded in laboratory settings, but studies reporting such cases revealed changes in ankle mechanics as early as 60 ms after initial contact.[32] Therefore, the initial 100 ms after landing may be decisive to determine safety and stability of the ankle joint. Our study revealed that at initial contact all participants presented a plantar flexed, inverted foot (Figure 2 A, C and E), moving towards dorsiflexion, abduction and eversion within the first 100 ms of contact. The increased ankle abduction and eversion joint work during this short time range after training may suggest specific adaptations to improve medio-lateral ankle stability when high vertical and lateral loads are applied. It has been speculated that the coordination in joint power and work may reflect muscle coordination patterns used to cope with the load at the initial contact.[33] It is noteworthy that there were no reductions in vertical and lateral forces or rates of force development, suggesting that the loads experienced during landing were similar before and after training. The lateral jump-landing task used in this study provided an additional challenge to medio-lateral postural stability during single-leg landing. Avoiding extra steps in such conditions demands effective strategies to accommodate joint loads, dissipate energy and maintain joint stability.[34,35] Therefore, WB training seems to optimize neuromuscular strategies to accommodate loads of the ankle joint.

The present study investigated motor coordination during lateral landing using NMF, which has also been recently used to describe the strategies for muscle recruitment in sports movements.[10,29,36] In the current study, NMF was used to quantify inter-muscular coordination during landing while reducing the dimensionality of the EMG data. Six modules were required to adequately describe the muscle activation involved in lateral landing. Other studies on human movement have described a smaller number of modules to represent muscle activation: Two modules for bench press[37]; three modules for breast stroke swimmers[38]; four modules for cycling and running[10,39] and five modules for 90º cutting maneuvers.[10] The elevated number of modules observed for landing may be related to the complex multi-joint coordination involved in load absorption and stabilizing body position in a short period of time.

Moreover, consistent dimensionality before and after training (i.e., number of motor modules) may emphasize that the neuromechanical requirements to perform landing remained similar following balance training. It is likely that the lack of specificity between training static balance on unstable surfaces and testing landing on one-leg from a lateral landing did not allow for substantial neuromuscular adaptations of landing performance.

Wobble board training changed the modular organization for the landing task, as evidenced in the lower similarity for M1 and M2. Muscles acting at the ankle joint (TA, PL, LG and MG) were contained predominantly in M1 prior to WB training. Following WB training, M1 consisted of muscles acting in the frontal plane (TA, PL), whereas M2 consisted of muscles acting in the sagittal plane (LG, MG). In other words, after training,gastrocnemius muscles were proportionally less active in the module with higher tibialis anterior and peroneus longus activation while the tibialis anterior and peroneus longus were proportionally less active in the module with main gastrocnemius activation. Similarly, peroneus longus, tibialis anterior and gastrocnemius muscles' secondary activations were lower after training in the module with predominant soleus activation. This selective activation of muscles controlling movement along specific degrees of freedom may have contributed to changes in the ankle joint work.

Computing residual muscle weightings may objectively describe whether one or multiple biomechanical sub-functions can be performed with reduced influence of non-related muscles, subsequently optimizing the motor pattern following training. Asaka et al.[40] trained individuals to stabilize their center of pressure location while standing on an unstable surface. Stronger muscle modes (termed modules in the present study) presented lower activation of less relevant muscles after practicing the task, with a concomitant reduction in the occurrence of co-contraction muscle modes. Our results corroborate these findings, suggesting that balance training induced re-organization of the spatio-temporal properties of existing modules[37,38,40] rather than changes in dimensionalty.

Previous studies have proposed several adaptation mechanisms to explain changes in motor performance and muscle activity following balance training. These adaptation mechanisms may vary from proprioceptive and sensorial adaptations to supraspinal adaptations[18,41]. Studies exploring the transfer of adaptations from balance training have shown reduced time to perform the shuttle-run test after four-weeks of BOSU balance training[42], faster reaction time to recruit muscles during forward perturbations to standing after six-weeks of wobble board balance training[17], as well as reduced loading of the knee joint while performing side-step cutting maneuvers after twelve-weeks of balance training using wobble boards, tilt boards, mini trampolines, dura discs, and Swiss balls.[43] Moreover, recently Oliveira et al.[29] have found a longer duration of muscle recruitment for the motor module related to the initial contact phase of side-cutting maneuvers during perturbations to balance after six-weeks of wobble board balance training. These findings suggest that adaptations from balance training may be transferred to sports movements, but the mechanisms underlying such improvements remain speculative. Our results suggest that changes in inter-muscular coordination and selective muscle recruitment may be a key factor for the adaptations to balance training. Moreover, these adaptations can influence joint mechanics and contribute to safer performance of challenging landing tasks. Future studies applying the presented methods to investigate different sports movements may contribute to increase our understanding of the mechanisms underlying the benefits of balance training.

This study proposed a novel protocol aiming to increase the postural control demands for landing from a lateral jump, which has been previously associated with greater joint moments.[6] Additionally, the target bar served to diverge participants' attention from the actual landing technique, focusing on reaching the bar as well as assuring consistent jump height before and after training. However, our protocol did not aim to mimic any specific game situation. Therefore, any suggestion that this type of training can lead to beneficial neuromechanical adaptations in game situations remains speculative. More studies are necessary to advance the understanding of the benefits of balance training on specific sports movements and for reducing injury incidences.

In summary, our results suggest that wobble board training can increase eversion and abduction ankle joint work. These mechanical changes may be directly related to modified modular organization of muscle recruitment in the early landing phase, in which there is specific spatio-temporal recruitment for plantar flexors and ankle evertors following training. Moreover, reductions in the modular activation of muscles not directly involved in mechanical sub-functions may illustrate an optimization in motor coordination following wobble board training.

PERSPECTIVES

This is the first study implementing non-negative factorization analysis to describe effects of balance training inter-muscular coordination in during lateral landing. This method shed some light on one of the potential mechanisms underlying the success of balance training in preventing lower limb injuries. Initially, by demonstrating the transferability of adaptations from training balance performed only using WBs to a landing task. Moreover, landing is a very typical task during training and competitions, and the implementation of methods to better understand motor coordination during this type of movement may assist in the detection of poor coordination. Single leg landing from a lateral jump induces greater mechanical loading for lateral braking, which will demand different neuromuscular control strategies compared to anterior-posterior landing. This suggests that such a task is more appropriate to indicate the existence of performance impairments [34,44] and to screen biomechanical and neuromuscular adaptations to balance training, especially when testing healthy participants. Future studies applying the presented methods to high-level athletes and injured athletes during and/or following rehabilitation protocols may contribute to further increase our understanding of the mechanisms underlying the benefits of balance training.

Conflict of interest: The authors declare that they have no conflict of interest.

Acknowledgement: This study was supported by the Center for Sensory-Motor Interaction (Aalborg University) and the Department of Mechanical and Manufacturing Engineering (Aalborg University).

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FIGURE LEGENDS

FIGURE 1. (A) Experimental set-up presenting the placement of EMG sensors (grey filled circles) connected with wires to the backpack with EMG amplifiers and the kinematic optical markers (black filled circles). (B) Protocol for lateral jump-landing performance, (C) Illustration of vertical ground reaction force (vGRF – solid line; gray circle indicating initial contact) and vertical displacement of the pelvis (vPelvic displacement – segmented line, black circles indicating maximum and minimum pelvic height), as well as the ankle angle displacement from a representative participant across 10 landings. (D) Representative EMG from one participant across 10 landings. DF = dorsiflexion; PF = plantarflexion; ABD = abduction; ADD = adduction; EVE = eversion; INV = inversion.

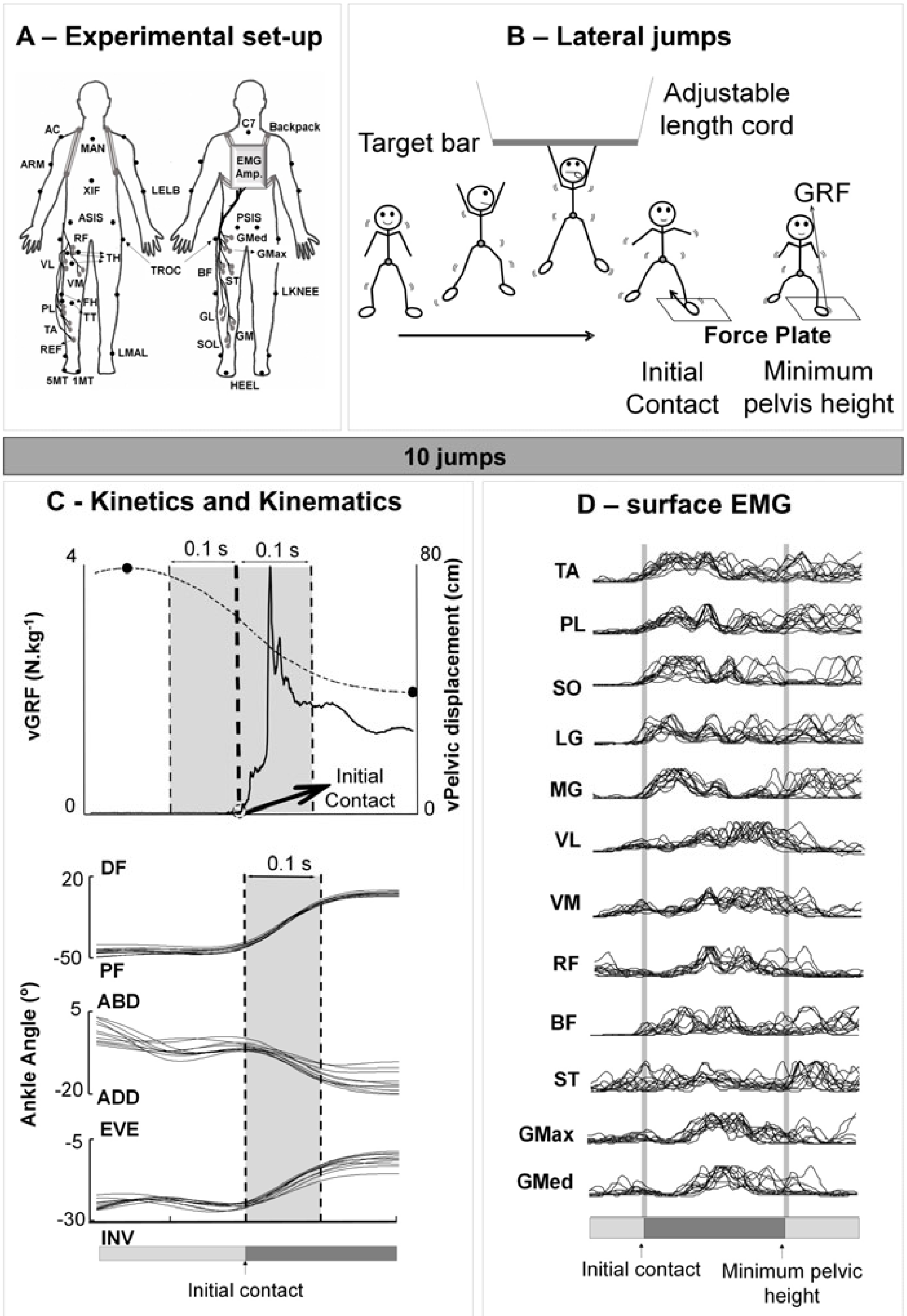
FIGURE 2. Mean (SD) ankle angle at initial contact (left) and ankle joint work (right) for dorsi/plantarflexion (DF/PF - A and B), abduction/adduction (ABD/ADD - C and D), eversion/inversion (EVE/INV - E and F) work for control (CG, dotted line) and training groups (TG, solid line) before (Pre) and after (Post) training. # indicates significant group-by-time interactions; * indicate significant difference Pre X Post training within group.

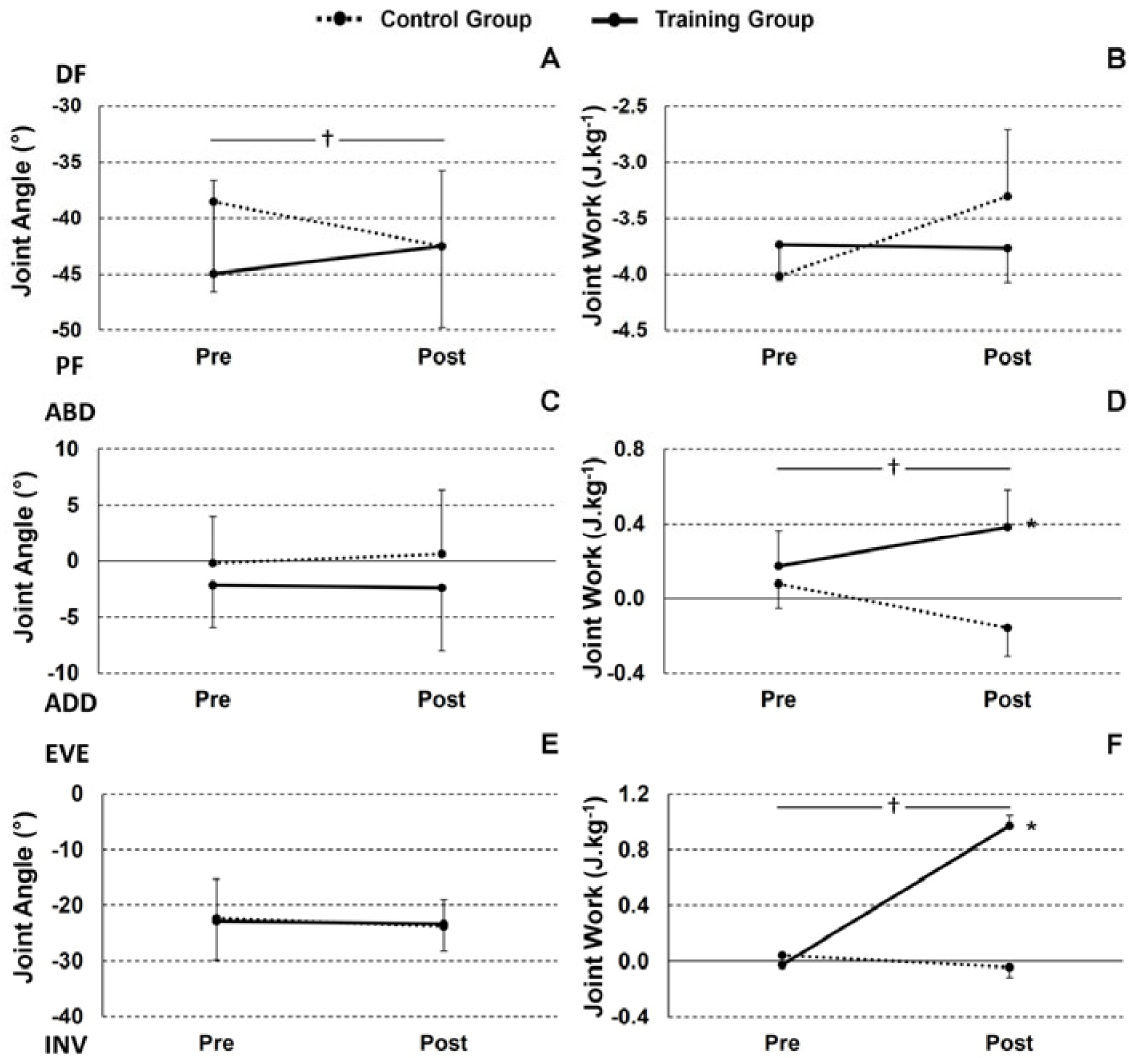
FIGURE 3. Motor modules (weighting coefficients) and activation signals from the concatenated EMG of the control group (*left*) and training group (*right*). We compared muscle weightings extracted from concatenated EMG across all participants Pre- (*black bars*) and Post-training (*red bars*) by computing similarities ('s' value on top of each couple of muscle weightings). In each panel, we plotted the mean activation signals (*thick lines*) and ± one standard deviation (*shaded areas*) respective to each motor module in the conditions Pre- (*black lines*) and Post-training (*red lines*) throughout the entire landing cycle. The first vertical grey line in the activation signal plots represents the instant of initial foot contact to the platform for landing, and the second grey line represents the instant of minimum pelvic height position after initial contact.

Figure 4. Mean (SD) similarity (*panel A*) of motor modules (MM) and activation signals (AS) between Pre- and Post-training conditions for the control group (CG, *grey bars*) and the training group (TG, *black bars*). The residual muscle weighting (B) are shown before (Pre) and after balance training (Post). † denotes significant group-by-time interactions. *denotes significant difference in relation to the MM similarity within group.

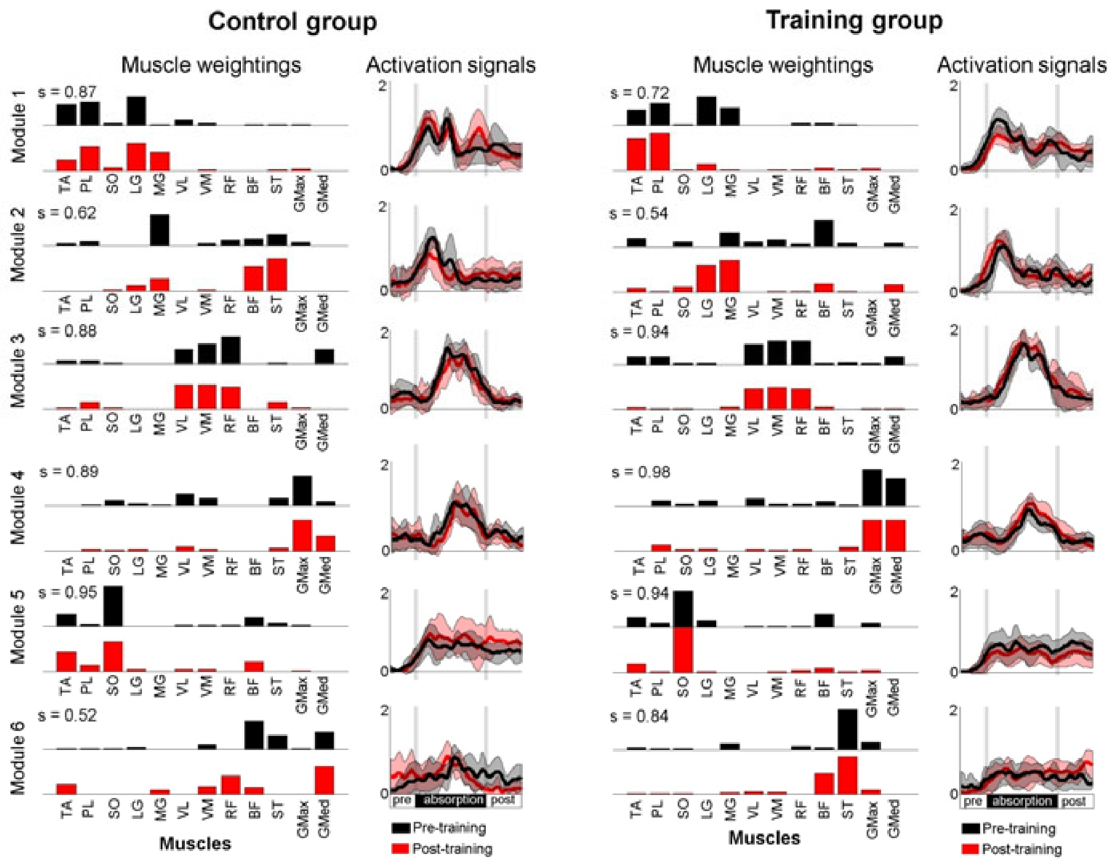
TABLE 1. Mean ±SD lateral jump height, vertical and lateral peak ground reaction forces (GRF), and rate of force development (RFD) of the control (CG) and training group (TG) before (Pre) and after (Post) training.

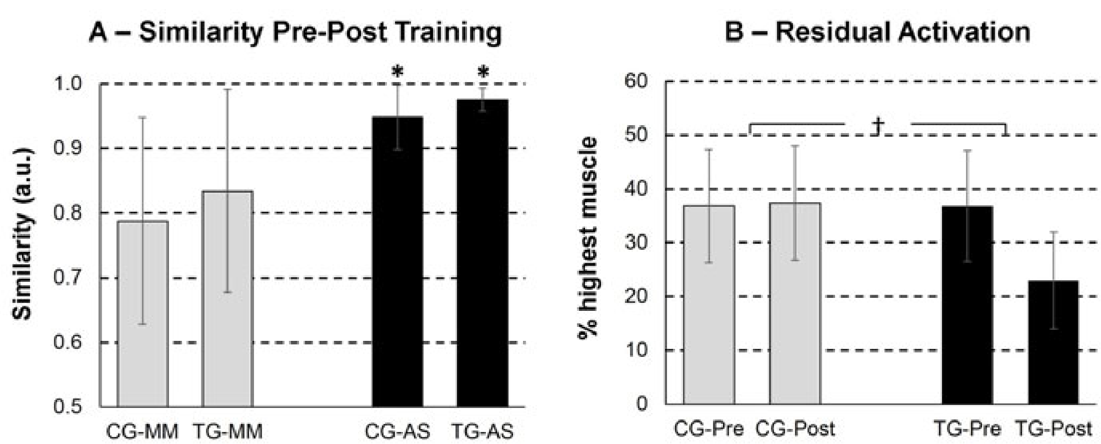
		Control Group	Training Group
Jump Height (cm)	Pre	32.5±5.0	35.3±5.0
	Post	30.9±5.0	35.±5.4
Vertical GRF ($N.kg^{-1}$)	Pre	3.6±0.4	3.8±0.6
	Post	3.7±0.6	3.8±0.7
Vertical RFD ($N.kg^{-1}.s^{-1}$)	Pre	148.2±36.7	150.9±40.4
	Post	168.8±63.0	160.3±52.3
Lateral GRF ($N.kg^{-1}$)	Pre	0.6±0.1	0.7±0.1
	Post	0.6±0.2	0.6±0.1
Lateral RFD ($N.kg^{-1}.s^{-1}$)	Pre	21.7±4.4	22.7±6.3
	Post	23.9±5.2	22.8±8.0


A – Experimental set-up
AC
MAN
ARM
XIF
LELB
ASIS
RF
VL
TH
VM
TROC
FH
PL
TT
TA
REF
LMAL
5MT 1MT
C7
Backpack
EMG Amp.
PSIS
GMed
GMax
BF
ST
LKNEE
GL
SOL
GM
HEEL
B – Lateral jumps
Adjustable length cord
Target bar
GRF
Force Plate
Initial Contact
Minimum pelvis height
10 jumps
C - Kinetics and Kinematics
0.1 s
0.1 s
4
80
vGRF (N.kg-1)
vPelvic displacement (cm)
0
0
Initial Contact
20
DF
-50
PF
5
ABD
-20
ADD
Ankle Angle (°)
-5
EVE
-30
INV
Initial contact
D – surface EMG
TA
PL
SO
LG
MG
VL
VM
RF
BF
ST
GMax
GMed
Initial contact
Minimum pelvic height



Control Group
Training Group
A
DF
-30
-35
-40
-45
-50
PF
Joint Angle (°)
Pre
Post
†
B
-2.5
-3.0
-3.5
-4.0
-4.5
Joint Work (J.kg⁻¹)
Pre
Post
C
ABD
10
5
0
-5
-10
ADD
Joint Angle (°)
Pre
Post
D
0.8
0.4
0.0
-0.4
Joint Work (J.kg⁻¹)
†
*
Pre
Post
E
EVE
0
-10
-20
-30
-40
INV
Joint Angle (°)
Pre
Post
F
1.2
0.8
0.4
0.0
-0.4
Joint Work (J.kg⁻¹)
†
*
Pre
Post


Control group
Training group
Muscle weightings
Activation signals
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
s = 0.87
s = 0.62
s = 0.88
s = 0.89
s = 0.95
s = 0.52
s = 0.72
s = 0.54
s = 0.94
s = 0.98
s = 0.94
s = 0.84
TA PL SO LG MG VL VM RF BF ST GMax GMed
Muscles
pre absorption post
Pre-training
Post-training


A – Similarity Pre-Post Training
Similarity (a.u.)
1.0
0.9
0.8
0.7
0.6
0.5
CG-MM
TG-MM
CG-AS
TG-AS
*
B – Residual Activation
% highest muscle
60
50
40
30
20
10
0
†
CG-Pre
CG-Post
TG-Pre
TG-Post